

SIZE CONSTRAINTS ON SELF IGNITION OF CHARCOAL BRIQUETS

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ABSTRACT

Self ignition is defined as thermal runaway due to internal exothermic reactions. Thomas' classic analysis of self heating to ignition led to laboratory-scale test methods identifying conditions under which spontaneous combustion is possible. These experimental techniques, as described e.g. in Beever's chapter in the second edition of the SFPE Handbook of Fire Protection Engineering, have considerable utility in fire-hazard assessment. The NFPA Fire Protection Handbook Table A-10 "Materials Subject to Spontaneous Heating" is incorrect and should be abandoned. As a practical example, the SFPE technique is applied here to the question: How large a pile of charcoal briquets is required for self heating to ignition? Correction factors for the Frank-Kamenetskii approximations are examined in detail. The data show that the largest commercially-available bag of charcoal briquets, 9 kg (20 lb.), cannot self ignite at an ambient temperature below 394 K (121°C or 250°F). All tested variations: size, different formulations, addition of water or dry wood, aging, and different bag configurations, raised this critical temperature even higher. At 25°C (77°F) these data show a bag of charcoal briquets would have to exceed the size of a typical house ($>10^3 \text{ m}^3$) to self ignite. Self ignition at ambient temperatures of bagged charcoal briquets in commercially available sizes is impossible.

KEYWORDS: Self heating, Spontaneous combustion, Spontaneous ignition, Charcoal, Briquets, Self ignition

NOMENCLATURE

A	Frequency factor, s^{-1}	t	Time, s
Bi	Biot number, hr/k , –	T	Temperature, K
c	Specific heat capacity, J/kgK		
E	Activation energy, J/mole	<u>Greek</u>	
h	Heat transfer coefficient, W/mK	α	Thermal diffusivity, $k/\rho c$, m^2/s
k	Thermal conductivity, $\text{W}/\text{m}^2\text{K}$	δ	Frank-Kamenetskii parameter, –
Nu	Nusselt No., hL/k_a , –	ϵ	RT/E , dimensionless inverse activation energy, –
P	$\ln(\rho QAE/kR)$, preexponential parameter	ρ	Mass density, kg/m^3
Pr	Prandlt No., ν/α , –	θ	Dimensionless temperature, $(E/RT_o^2)(T-T_o)$, –
Q	Reaction enthalpy, J/kg	τ	Thickness, mm
r	Characteristic dimension, m	ν	Kinematic viscosity, m^2/s
R	Universal gas constant, 8.31 J/moleK		

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Subscripts

<i>a</i>	Air
<i>c</i>	Critical
<i>e</i>	Effective
<i>m</i>	Mean

<i>o</i>	Ambient (or oven)
<i>p</i>	Paper (bag)
<i>r</i>	Radiative
<i>s</i>	Surface or solid
∞	Limit value as $Bi \rightarrow \infty$ and $\epsilon_o \rightarrow 0$

1. INTRODUCTION

Problem Statement

Self heating is the process by which materials achieve temperatures higher than ambient as a result of internal exothermic reactions. Ignition is defined as thermal runaway. If the internal temperature rise is high enough to cause thermal runaway, the system is said to be capable of self heating to ignition [1-4]. Self heating to ignition, self ignition, and spontaneous combustion are synonymous.

Thermal runaway occurs when local heat generation exceeds local heat loss. For porous, permeable and oxidizable materials, this battle between exothermic chemistry and transport physics occurs in each volume element. Exothermicity has its best chance of winning at the most adiabatic point, i.e., at the center. How adiabatic the central volume element is depends on the distance to the boundary and the temperature there. Thus, the tendency to self heat has an inherent dependence on system size and boundary temperature. It is not a material property, as flashpoint is, and therefore no quantification of a materials' self-ignition hazard is possible without incorporating system size and ambient temperature.

In the 1950s, the National Fire Protection Association developed an excellent classification scheme for ranking the fire hazard of flammable and combustible liquids as IA through IIIB, in order of increasing flashpoint, which is still in use today [5]. Buoyed by this success with liquids, they attempted a similar classification for solids, ranking the tendency of various materials to self heat from "very slight" to "high," but neglecting the critical roles of system size and exposure temperature on self heating. The table, "Materials Subject to Spontaneous Heating," first appeared in the twelfth (1962) edition of the NFPA Fire Protection Handbook. The NFPA "Committee on Spontaneous Heating and Ignition," which generated that table with little underlying scientific analysis, has been disbanded [6]. However, the original incorrect 1962 table remains unaltered in the current edition of the NFPA Fire Protection Handbook [6]. Table A-10 should also be abandoned, since it misleads fire investigators by failing to identify the inherent connection between system size and self ignition. They consequently may erroneously claim spontaneous combustion as a fire cause [7, 8]. Ironically, the NFPA also publishes the SFPE Handbook of Fire Protection Engineering with an outstanding chapter, "Self-Heating and Spontaneous Combustion," by Beever describing experiments to determine the influence of size and temperature on materials' self-heating characteristics [3]. Charcoal, which is listed as having a "high tendency to spontaneous heating" in the old NFPA table [6], is examined here using the SFPE method. The question quantitatively addressed is: What critical sizes must a pile of charcoal briquets exceed, as a function of ambient temperature, for self ignition to occur?

Frank-Kemenetskii Parameter

The energy equation applicable to self heating, with the approximation of a single Arrhenius generation term, is

$$\rho c \partial T / \partial t = k \nabla^2 T + \rho Q A \exp(-E/RT), \quad (1)$$

where energy storage is on the left and physical transport and chemical generation are on the right and the symbols are defined in the nomenclature. Four approaches to solving this equation for $T(t)$ are available in the combustion literature. Direct integration is possible with modern computers [9]. The classic isothermal Semenov model [10-12] is inappropriate for fire hazard analyses because it fails to account for internal heat transport. However, Chen [13,14] has developed an exciting new experimental method, exploiting transient isothermicity, which shows promise for reducing the number and duration of experiments required to obtain self-heating kinetic parameters [15,16].

Here our approach follows Frank-Kamenetskii [4], who examined the steady limit of Eq. (1). A simple outline of his method where the energy equation then becomes a balance between conduction and generation is given here. See Bowes [2] for more detail. It is assumed that the material is sufficiently porous and reactive that adequate fuel and oxygen are available throughout self heating to ignition. The boundary conditions are symmetry at the origin, in the center of the system, and a balance between conduction and convection on all bounding surfaces, which becomes $T|_s = T_o$ in the limit of large Biot number, $Bi = hr/k \gg 1$. The activation energy is also assumed sufficiently large that, with $\epsilon \equiv RT/E$, $\epsilon_o \ll 1$. The argument of the exponential in the generation term, where $\theta \equiv (E/RT_o^2)(T - T_o)$ is the dimensionless temperature, can then be approximated as

$$E/RT = 1/\epsilon_o - \theta / (1 + \epsilon_o \theta) \approx 1/\epsilon_o - \theta. \quad (2)$$

Thus Eq. (1) becomes

$$\nabla^2 T + (\rho Q A / k) \exp(-1/\epsilon_o) \exp(\theta) = 0. \quad (3)$$

Nondimensionalizing on the maximum spatial coordinate, r , and introducing θ then gives

$$\nabla^2 \theta + \delta \exp(\theta) = 0, \quad (4)$$

where the coefficient of the exponential is called the Frank-Kamenetskii parameter,

$$\delta \equiv (\rho Q A / k) (E r^2 / R T_o^2) \exp(-1/\epsilon_o). \quad (5)$$

For any given geometry, the governing Eq. (4) is solved subject to

$$\nabla \theta|_0 = 0 \quad \text{and} \quad \theta|_s = 0, \quad (6)$$

with δ as a parameter [2, 17]. The largest δ for that geometry which produces a stable steady solution is called the critical Frank-Kamenetskii parameter, δ_c . If $\delta > \delta_c$, self ignition occurs, i.e., no steady solution exists. A practical review of the critical parameters for several geometries and the corrections required for proper application is given in Beever's chapter of the SFPE Handbook of Fire Protection Engineering [3].

Once δ_c is known from independent calculations, the kinetic parameters in Eq. (1) can be obtained experimentally for any material. A series of oven experiments, using different size samples, r , in which the oven temperature, T_o , is varied will define a critical initial oven temperature, T_{oc} , above which self ignition occurs; below, it does not. Rearrange Eq. (5) as

$$\ln \delta_c T_{oc}^2 / r^2 = \ln (\rho Q A E / k R) - E / R T_{oc} = P - E / R T_{oc}. \quad (7)$$

A plot of the lefthand side of Eq. (7) versus the experimental $1/T_{oc}$ determines the kinetic

parameters, P and E/R , as intercept and slope. The linearity of the plot also assesses the validity of the Frank-Kamenetskii assumptions. (See e.g. Fig. 3.) Note that Eq. (5) also provides a self-ignition map for any given system. Solving Eq. (7) for $r(T_{oc})$ gives

$$r = \delta_c^{0.5} T_{oc} \exp(-0.5P) \exp(0.5E/RT_{oc}). \quad (8)$$

Once δ_c , E/R and P are known from calculations and experiment, Eq. (8) gives, as a function of temperature, the critical size above which a material will self ignite. Only such a diagram can quantify the system's self-ignition hazard. (See e.g. Fig. 4.) That hazard is the result of the delicate balance between chemical heat generation and physical heat loss so that size, r , shape, δ_c , ambient temperature, T_o , and material properties, P and E/R , all play a role.

Outline

The next section describes experiments determining T_{oc} as a function of r for formulations commonly used in charcoal briquets. The data analysis section gives an evaluation of δ_c for these experimental conditions (shape, size, Bi and ϵ_o). The discussion section determines P and E/R for several charcoals and draws conclusions.

2. EXPERIMENTS

The shape and size of the briquets used is shown in Fig. 1. The briquets averaged 8% water which is typical of commercial products. The three briquet formulations tested were: lignite char 90%, other 10%; wood char 85%, other 15%; and wood char 85%, wood (mesquite) 5%, and other 10%. A lignite char briquet was included for comparison with the more common wood char briquets. The average single-briquet density was 800 kg/m³. The T_{oc} data were obtained in a Fisher Isotemp model 350 oven. The horizontal air velocity across the oven varied approximately linearly from 0.9 m/s at the bottom to 1.2 m/s at the top. The oven and sample temperatures were measured using 0.5 mm diameter type K thermocouples. The measured temperatures were accurate to approximately 1 K (2°F) and the oven chamber with no sample present was isothermal to within approximately 1 K (2°F) over the temperature range used here.

The charcoal samples were contained in stainless steel mesh baskets with thermocouples placed at various locations to record the spatial dependence of the temperature histories. During self heating the surface temperature was below the center temperature with the difference increasing as the sample size increased. The presence of bags slightly lowered T_{oc} since the permeable bag material, consisting of approximately 1mm of ordinary kraft paper, allows oxygen transfer but inhibits convective heat transfer. The briquets were poured into the basket or bag and lightly jiggled to give a uniform compaction of ~50% void. The briquets themselves are extremely porous, with measured surface areas of ~80 m²/g, so that oxygen has ready access to central reactive sites. The smallest sample tested consisted of a single briquet, as shown in Fig. 1, with the largest a 9 kg (20 lb) bag. Samples were placed in the oven after it had been heated to the test temperature, T_o . If thermal runaway did not occur, the experiment was repeated at a higher temperature with a fresh sample. If thermal runaway occurred, the experiment was repeated at a lower temperature with a fresh sample. In this way, convergence on the actual value of T_{oc} for each size tested was achieved to

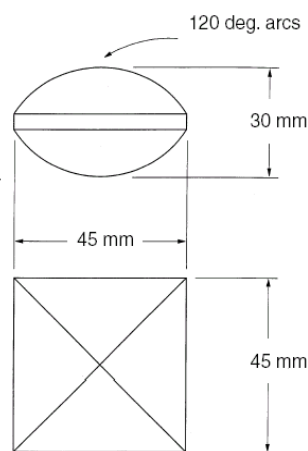


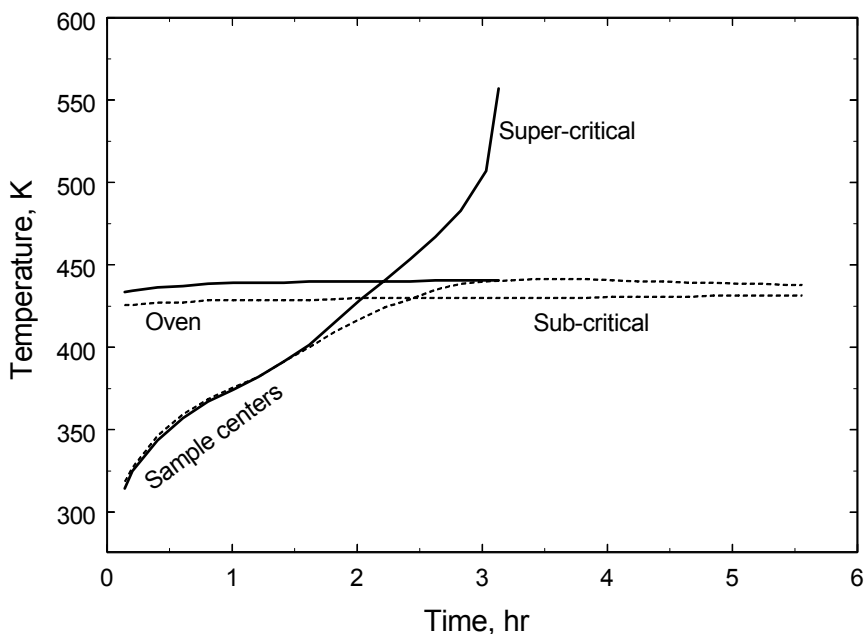
Figure 1. Size and shape of a single briquet.

approximately one percent accuracy. The value reported for T_{oc} was taken as the mean of the highest temperature at which there was no ignition and the lowest temperature at which ignition occurred.

When thermal runaway did not occur, the sample temperature reached a maximum a few degrees higher than the oven temperature [3] and would then asymptotically approach the oven temperature. Examples of sub-critical and super-critical temperature-time plots for bagged wood char with wood briquets in a 0.1 m (4 in.) cube are shown in Fig. 2. The iteration required by this experimental method is not efficient, especially for the larger sample sizes since these require long times (days) to reach their temperature maxima. New methods are much faster [13-16]. The experimental values of T_{oc} for the various systems are listed in Table 1. In this context, T_{oc} may be considered to be the minimum ambient temperature that must be maintained for ignition to occur. Results are included for the more common wood-based charcoal both with and without bags and for lignite-based charcoal in bags only.

Briquets were also subjected to high-humidity conditions. After approximately one month in an open basket at 305 K and 85% relative humidity, the average moisture content was 12%. There was no significant difference between the high water content T_{oc} values and those in Table 1, with a slight increase (3 K) for the high water content briquets, possibly due to increased conductivity. There was also no significant difference between charcoal made from different wood species in briquets of high wood char content. Aging the briquets for a year increased T_{oc} slightly (10 K), presumably due to fewer active sites or species. Increasing the wrapping size also increased T_{oc} , e.g., 1 briquet in a 2.3 kg (5 lb.) bag gave a T_{oc} 10 K higher than 1 briquet surrounded tightly by bag material. In all tests, the lowest temperature at which ignition was observed was $T_{oc} = 394$ K (121°C or 250°F).

Figure 2. Oven and sample-center temperature histories for a sub-critical test (---) at an oven temperature of ~430K and a super-critical test (—) at an oven temperature of ~440K. Both samples are bagged wood char with wood in a 0.1 m (4 in.) cubic



Formula and System	Size (mm) r or r / z	T_{oc} (K)
Lignite Char		
1 briquet (sphere)	20	460
0.1 m (4 in.) basket (cube)	51	433
0.15 m (6 in.) basket (cube)	76	422
2.3 kg (5 lb.) bag (cylinder)	84 / 114	421
4.5 kg (10 lb.) bag (cylinder)	102 / 165	416
9 kg (20 lb.) bag (cylinder)	130 / 216	412
Wood Char		
1 briquet (sphere)	20	461
0.1 m (4 in.) basket (cube)	51	420
2.3 kg (5 lb.) bag (cylinder)	84 / 114	404
9 kg (20 lb.) bag (cylinder)	130 / 216	394
Wood Char with Wood		
1 briquet (sphere)	20	463
0.1 m (4 in.) basket (cube)	51	430
9 kg (20 lb.) bag (cylinder)	130 / 216	395
Wood Char (bagless)		
1 briquet (sphere)	20	468
0.1 m (4 in.) basket (cube)	51	431
0.15 m (6 in.) basket (cube)	76	418
0.23 m (9 in.) basket (cube)	114	408
0.3 (12 in.) basket (cube)	152	403
Wood Char with Wood (bagless)		
1 briquet (sphere)	20	473
0.1 m (4 in.) basket (cube)	51	440
0.3 (12 in.) basket (cube)	152	409

Table 1. All systems were bagged unless labeled bagless. The first column lists the formulation and shape. The second gives the radius or cube half-side and radius/cylinder half-height. The final column is the experimental critical temperature found here for each system.

3. DATA ANALYSIS

To extract the kinetic parameters in Eq. (7) from the data in Table 1, it is necessary to correct δ_c for the approximations of $\epsilon_o \ll 1$ and $Bi \gg 1$ [3]. The primary control on δ_c is exercised by the geometry, so $\delta_{c\infty}$ is defined as $\delta_c(\text{shape})$ in the limit of no corrections. Bowes [2] and Beever [3] give the following $\delta_{c\infty}$: Sphere, 3.32; Cube, 2.52; Finite Cylinder, $2 + 0.84(r/z)^2$, where r is the radius and z is the half height. Methods for finding δ_c in more complex geometries are available [17]. The corrections for ϵ_o and Bi are then introduced as

factors,

$$\delta = \delta_{c_{\infty}} \cdot \delta_c(\epsilon_o) / \delta_{c_{\infty}} \cdot \delta_c(Bi) / \delta_{c_{\infty}}. \quad (9)$$

Boddington suggests (see Eq. (8) of Beever [3])

$$\delta_c(\epsilon_o) / \delta_{c_{\infty}} = 1.0 + 1.07 \epsilon_o. \quad (10)$$

Iteration here resulted in a 2 to 4 percent increase in δ_c due to this effect. Thomas [1] gives $\delta_c(Bi) / \delta_{c_{\infty}}$ for spheres, infinite cylinders and slabs. All of his curves are well approximated with Barzykin's expression (see Eq. (7) of Beever [3]):

$$\delta_c(Bi) / \delta_{c_{\infty}} = 0.5 Bi \left((Bi^2 + 4)^{0.5} - Bi \right) \exp \left[\left((Bi^2 + 4)^{0.5} - Bi - 2 \right) / Bi \right]. \quad (11)$$

Thus for these experiments, δ_c will be known once Bi is determined.

The Fisher oven had a cross flow hot air velocity of $U = 1$ m/s, which with a kinematic viscosity, $\nu \approx 3.5 \times 10^{-5}$ m²/s, for air at 400K, and L approximated as half the maximum perimeter, as shown in Table 2, gives Reynolds numbers, $Re = UL/\nu$ in the laminar range, 6×10^3 to 3×10^4 . The Prandlt number for hot air is $Pr = 0.7$. A convective heat transfer coefficient, h_a can be estimated from the average Nusselt number over a flat plate,

$$h_a L / k_a = Nu = 0.67 Re^{1/2} Pr^{1/3}, \quad (12)$$

where the thermal conductivity of hot air is $k_a \approx 0.035$ W/m²K [18]. The single briquet shown in Fig. 1 was approximated on a volume basis as a 20 mm radius sphere with $L=D$ and $Nu = 2 + 0.6 Re^{1/2} Pr^{1/3}$. Radiation can be linearized [18] using $h_r = 4F\sigma T_m^3$, where F is a shape and surface emissivity factor, here $F \approx 1$, $\sigma = 5.67 \times 10^{-8}$ W/m²K⁴ is the Stefan-Boltzmann constant, and T_m is the mean temperature of the interacting surfaces. The total heat transfer coefficient is then $h = h_a + h_r$.

The bagged or basketed system was modeled as a porous medium with an effective thermal conductivity, $k_e = \Phi k_a + (1 - \Phi)k_s$, where Φ is the void (air) volume fraction and $k_s = 0.26$ W/mK is the briquet's thermal conductivity. Φ was measured as ≈ 0.5 , so that $k_e \approx 0.15$ W/mK. Similarly, $\rho_e \approx 400$ kg/m³. k_s was measured by tracking the approach to room temperature of preheated or pre-cooled briquets in a high-velocity air stream. The briquet specific heat capacity was also obtained in calorimetry experiments as $c_p = 1.2$ kJ/kg K.

Formula and System	$10^3 T_{oc}^{-1}$ (K ⁻¹)	L (mm)	h_a, h_r		Bi	$\frac{\delta_c(Bi)}{\delta_{c_{\infty}}}$	δ_c	$\delta_c T_{oc}^2 r^{-2}$ (K ² /m ²)
			(W/m ² K)					
Lignite Char								
1 briquet (sphere)	2.17	40	18	22	2.3	0.52	1.7	871
0.1 m (4 in.) basket (cube)	2.31	250	7	18	7.2	0.80	2.0	143
0.15 m (6 in.) basket (cube)	2.37	370	6	17	9.8	0.85	2.1	66
2.3 kg (5 lb.) bag (cylinder)	2.38	400	5	17	11	0.86	2.1	53

4.5 kg (10 lb.) bag (cylinder)	2.40	530	5	16	12	0.88	2.0	34
9 kg (20 lb.) bag (cylinder)	2.43	690	4	16	15	0.91	2.1	21
Wood Char								
1 briquet (sphere)	2.17	40	18	22	2.3	0.53	1.8	930
0.1 m (4 in.) basket (cube)	2.38	250	7	17	6.8	0.80	2.0	154
2.3 kg (5 lb.) bag (cylinder)	2.48	400	5	15	9.7	0.86	2.1	48
9 kg (20 lb.) bag (cylinder)	2.54	690	4	14	14	0.91	2.1	19
Wood Char with Wood								
1 briquet (sphere)	2.16	40	18	23	2.4	0.53	1.8	940
0.1 m (4 in.) basket (cube)	2.33	250	7	18	7.2	0.80	2.0	142
9 kg (20 lb.) bag (cylinder)	2.53	700	4	14	14	0.91	2.1	19
Wood Char (bagless)								
1 briquet (sphere)	2.14	40	18	23	3.1	0.61	2.0	1090
0.1 m (4 in.) basket (cube)	2.32	250	7	18	8.6	0.83	2.1	147
0.15 m (6 in.) basket (cube)	2.39	370	6	17	11	0.88	2.2	67
0.23 m (9 in.) basket (cube)	2.45	550	5	15	15	0.91	2.3	29
0.3 (12 in.) basket (cube)	2.48	550	4	15	19	0.94	2.4	17
Wood Char with Wood (bagless)								
1 briquet (sphere)	2.11	40	18	27	3.5	0.61	2.0	1100
0.1 m (4 in.) basket (cube)	2.27	250	7	20	9.1	0.84	2.1	155
0.3 (12 in.) basket (cube)	2.44	730	4	16	20	0.94	2.4	17

Table 2. Calculations of the Biot number corrections. All samples were bagged unless labeled bagless. The first column lists the formulation and shape. The final column is $\delta_c T_{oc}^2 r^{-2}$ in K^2/m^2 for plotting in Fig. 3.

An additional correction is required for the bagged systems. Thomas [1] suggests that an insulating sheath can be taken into account by modifying h by dividing it by $1 + Bi_p$ where $Bi_p = \tau h / k_p$. Here $\tau = 1$ mm and $k_p = 0.13$ W/mK are the thickness and thermal conductivity of the paper sheath. The final calculated values of δ_c for these experiments are listed in Table 2. The estimated error in δ_c is 10% which Beever [3] suggests corresponds to

a 5% error in critical size or a <1% error in critical temperature.

4. DISCUSSION

Kinetic Parameters

Figure 3 shows semilog plots of $\delta_c T_{oc}^2 / r^2$ (K^2 / cm^2) vs. $10^3 / T_{oc}$ (K^{-1}) for the five systems in Table 2. Here the units of r are changed from m to cm for ease of scaling. The slope gives the activation energy, E/R , and the intercept provides P , the other thermochemical properties in Eq. (7). The good linearity shown justifies the Frank-Kamenetskii assumptions for charcoal briquets. Table 3 gives the E/R and P parameter values for the five formulations along with literature values of a comparable material. These results are in good agreement with the literature [2, 9, 15] for char reactions. Since the range of experiments includes the largest commercial bag size, no extrapolation is needed and it can be confidently stated that these are the pertinent self-ignition reactions [2, 3]. The higher activation energy for lignite char is also consistent with the literature [9]. The higher E/R for the bagless systems may be due to higher heat loss in the interstices causing higher T_{oc} at the intermediate sizes.

Other Effects

Bacterial growth can play an important role in the self ignition of hay, grass or wood chips [2]. In the case of charcoal briquets, however, the cut off temperature for bacterial activity, which according to Walker [19] is 80°C (175°F), is well below the minimum required ignition temperature of 120°C (250°F). The maximum temperature increase from water adsorption by charcoal briquets is < 4°C (7°F). Values of the heat capacity, $c_p = 1.2$ kJ/kgK, and latent heat of wetting, $\Delta H_{wetting} = 5.2$ kJ/kg (wood) and = 4.1 kJ/kg (lignite) were obtained in a calorimeter constructed from a lab dewar, insulating cap, thermometer, and immersion heater of known resistance. The calorimeter constant was determined by applying measured voltages to the immersion heater for measured periods of time. Samples were ground prior to being added to the calorimeter.

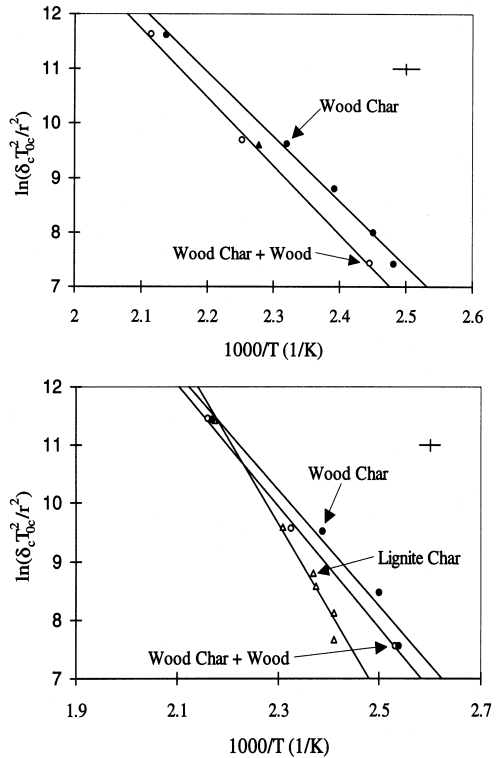


Figure 3. Plot of Eq. (7) for: A) the two bagless charcoals; and B) the three bagged charcoals. The ordinate has T_{oc} in K and r in cm, while the abscissa is in K^{-1} . The slope is $-E/R$ and the intercept as $T \rightarrow \infty$ is P . The error bar indicates a $\pm 1\%$ uncertainty in T_{oc} with a $\pm 10\%$ uncertainty in the ordinate, primarily due to δ_c .

Vacuum-degassed samples, held at <1 mm Hg for 12 hours, gave higher latent heats of wetting, 21 kJ/kg (wood) and 31 kJ/kg (lignite). Heats of wetting were determined by observing the initial temperature rise after the sample had been placed in the calorimeter. Heat capacities were determined by noting the temperature rise after known amounts of electrical work were added via the immersion heater. These data suggest a maximum temperature increase due to wetting of only 4°C (7°F) in the vacuum-degassed samples. Such highly dehydrated charcoal would not be encountered in normal use outside the laboratory. These results are in good agreement with the literature [2, 20].

Material	E/R [K]	P [K ² /cm ²]	QA [GW/kg]
Lignite Char	14700	43.5	2.0x10 ⁶
Wood Char with Wood (bagless)	12600	38.2	12x10 ³
Wood Char (bagless)	11900	37.1	4.1x10 ³
Wood Char with Wood	10400	33.9	190
Wood Char	10000	33.1	89
Cooked Douglas fir chips [15, 16]	9700	21.6	690

Table 3. This table summarizes the kinetic parameters determined in this experimental study. QA was obtained with $\rho_e/k_e=2.67 \times 10^3$ kgK/Wm². It is not possible to extract A without separate experiments to determine Q for the global self-ignition reaction, which is not the charcoal heat of reaction [21].

Self-Ignition Map

Using the results from Table 3 for the bagged wood char formulation, the one with the lowest T_{oc} in Eq. (8) with a conservative constant $\delta_c = 2.3$ gives the following relation between critical radius and minimum ambient ignition temperature,

$$r_c = 9.85 \times 10^{-10} T_{oc} \exp\left(\frac{5000}{T_{oc}}\right), \quad (13)$$

where r_c is in m and T_{oc} is in K. The relation between critical size and critical temperature is best illustrated by a map such as Fig. 4 which plots Eq. (13) as $r_c(T_{oc})$, the dividing line between small, cold systems which cannot self ignite and large, hot ones that can. All other formulations and configurations would have a critical interface above the one drawn for the bagged wood char formulation. The region where self ignition can occur is shown in Fig. 4 to exclude commercial sizes by a wide margin. The largest commercially available bag has a volume of 0.023 m³. Using the $r_c = 5.7$ m given by Eq. (13) at $T_c = 298$ K (25°C, 77°F) as a cube half-side gives $V_c \sim 1500$ m³, assuming the global self-ignition reaction remains the same for that large a pile size. At $\rho_e \approx 400$ kg/m³, this corresponds to 6×10^5 kg, over a million pounds, of charcoal briquets. So self-heating to ignition could only occur for a charcoal briquet pile over 60,000 times larger than the largest commercially available bag. Stacked charcoal briquets the size of a house 10 m high, broad, and long would not be large enough to self ignite at ambient conditions. These results confirm, however, possible self ignitions in exceptionally large, $r > 6$ m, charcoal storage or shiphold piles [2].

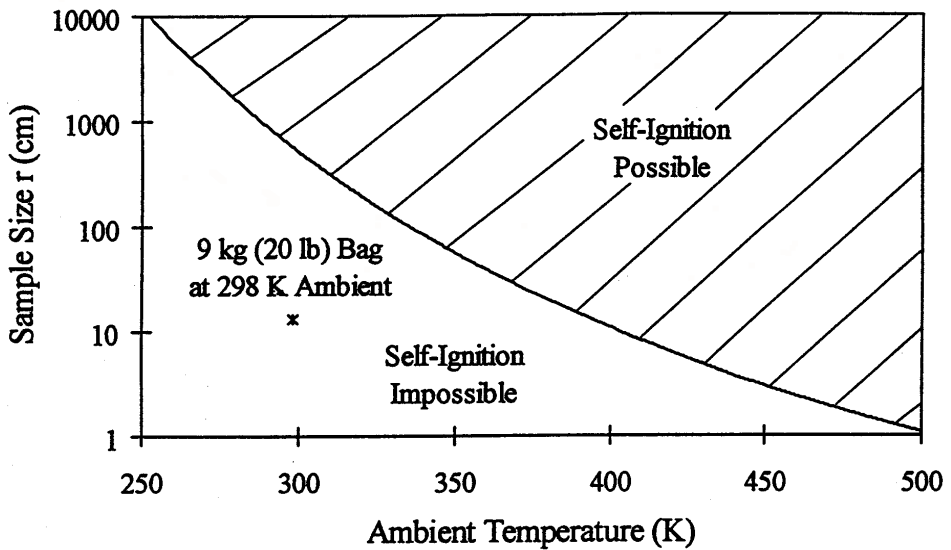


Figure 4. Stability map for bagged wood char defining the region in sample size-ambient temperature space where self ignition of charcoal briquets is impossible. The critical boundary is given by Eq. (13). Note that a 9 kg (20 lb.) bag at ambient temperature (298K) is well within the impossible to self-ignite zone.

4. CONCLUSIONS

1. A temperature of at least 394 K (121°C, 250°F) is required for self ignition of charcoal briquets to occur in the largest commercially available bag size, 9 kg (20 lbs.).
2. The minimum ambient temperature required for ignition increases for smaller sample sizes, for samples containing lignite char, for wet samples, for samples not enclosed in bags, and for partially filled bags.
3. Future work with experiments employing recently developed methods [13-17] for determining the self-ignition parameters of these and other charcoal systems would provide interesting comparisons.
4. Spontaneous combustion of bagged charcoal briquets in commercially available sizes is impossible under any normal ambient conditions.

REFERENCES

1. Thomas, P.H., "Self-heating and Thermal Ignition - A Guide to its Theory and Application," in *Ignition, Heat Release, and Noncombustibility of Materials*, ASTM STP 502, ASTM, Philadelphia, PA, 1972, pp. 56-82.
2. Bowes, P.C., *Self-heating; Evaluating and Controlling the Hazards*. Building Research Establishment, HMSO Books, London, England, 1984.
3. Beever, P.F., "Self-Heating and Spontaneous Combustion," in *The SFPE Handbook of Fire Protection Engineering*, 2nd ed., P.J. DiNenno, ed., NFPA, Quincy, MA, 1995, pp 2-180 to 2-189.
4. Frank-Kamenetskii, D.A., *Diffusion and Heat Transfer in Chemical Kinetics*, 2nd Ed. trans. ed. J.P. Appleton, Chap. 6, Plenum Press, New York, 1969.

5. NFPA, *Fire Protection Handbook*, 18th ed., Quincy, MA, 1997, pp 4-59 to 4-69.
6. *Ibid*, pp A-13 to A-16.
7. Roblee, C.L., "The Hazards of Charcoal Briquets," *Wisconsin Char Patterns*, 8, April-June 1982. See also Roblee, C.L., McKechnie, A.J., Lundy, W., *The Investigation of Fires*, 2nd ed., Prentice Hall: New Jersey, 1989, p59.
8. Anon, "Spontaneous Ignition of Charcoal," *Fire Journal*, **67**:4, 70, 1973.
9. Handa, T., Morita, M., Sugawa, O., Ishii, T., and Hayashi, K., "Computer Simulation of the Spontaneous Combustion of Coal Storage," *Fire Science and Technology*, **3**:1, 13-24, 1983.
10. Kanury, A. M., *Introduction to Combustion Phenomena*, Chapter 6, New York: Gordon and Breach, 1975.
11. Essenhigh, R.H., Misra, M., and Shaw, D.W., "Ignition of Coal Particles: A Review," *Combustion and Flame*, **77**:1, 3-30, 1989.
12. Krishnaswamy, S., et al., "Low Temperature Oxidation of Coal," (in three parts), *Fuel*, **75**, 333-362, 1996.
13. Chong, L. V., Shaw I.R., and Chen, X.D., "Thermal Ignition Kinetics of Wood Sawdust Measured by a Newly Devised Experimental Technique," *Process Safety Progress*, **14**:4, 266-270, 1995.
14. Chen X. D., Chong, L. V. "Some Characteristics of Transient Self-heating Inside an Exothermically Reactive Porous Solid Slab." *Process Safety and Environmental Protection: Transactions of the Institution of Chemical Engineers, Part B* **73**:101-107, 1995.
15. Cuzzillo, B.R. and Pagni, P.J., "The Myth of Pyrophoric Carbon," *Fire Safety Science—Proceedings of the Sixth International Symposium*, ed. Curtat, M., IAFSS, 2000, pp. 301-312.
16. Cuzzillo, B.R., *Pyrophoria*, Ph.D. Dissertation, Mechanical Engineering Department, University of California at Berkeley, 1997.
17. Boddington, T., Gray P., and Harvey, D.I., "Thermal Theory of Spontaneous Ignition: Criticality in Bodies of Arbitrary Shape," *Phil. Trans. Roy. Soc.*, London, **270**, 467-506, 1971.
18. Incropera, F.P., and Dewitt, D.P., *Fundamentals of Heat and Mass Transfer*, 4th ed, John Wiley and Sons, New York, 1996.
19. Walker, I.K., "The Role of Water in Spontaneous Combustion of Solids," *Fire Resesarch Abstracts and Reviews*, **9**:1, 5-22, 1967.
20. Nordon, P. and Bainbridge N.W., "Heat of Wetting of a Bituminous Coal," *Fuel*, **62**, 619-621, 1983.
21. Sugawa, O., "Short Communication on Self-Ignition of Potato Chips Waste," *Fire Science & Technology*, **12**:1, 1-6, 1992.